CHAPTER 11

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE US-AFFILIATED ISLANDS OF THE PACIFIC AND CARIBBEAN

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CHAPTER SUMMARY

Regional Context

This section deals with the US-affiliated islands of the Caribbean and Pacific. Included are Puerto Rico and the US Virgin Islands in the Caribbean and the Hawaiian Islands, American Samoa, the Common-wealth of the Northern Mariana Islands, Guam, the Federated States of Micronesia, the Republic of the Marshall Islands, and the Republic of Palau in the Pacific. The latter three are independent states in free association with the United States. Hawaii became the 50th state of the US in 1959. The Virgin Islands, Guam, and American Samoa are US territories. The Northern Mariana Islands and Puerto Rico are commonwealths.

Islands contain diverse and productive ecosystems, and include many specialized and unique species. Many islands are facing the stresses of rapid human population growth, increasing vulnerability to natural disasters, and degradation of natural resources. Droughts and floods are among the climate extremes of most concern as they affect the quality of water supplies in island communities and thus can have significant health consequences. Due to their small size and isolation, many islands face chronic water shortages and problems with waste disposal. Some are facing a species extinction crisis; for example, the Hawaiian Islands have the highest extinction rate of any state in the nation. Biological invasion and habitat destruction seem to be the primary causes of the extinction crisis. For most island communities, transportation and other social infrastructure and economic activities are located near the coast, making them highly vulnerable to storm events and sea-level fluctuations. Over-harvesting of reef organisms is a serious issue in parts of the Pacific.

Climate of the Past Century

Over the 20th century, average annual air temperatures in the Caribbean islands have increased by more than 1°F (0.6°C). Average annual air temperatures in the Pacific Islands have increased by about 0.4°F (0.2°C).

Globally, sea level has risen by 4 to 8 inches (10-20 cm) in the past 100 years, with significant local variation. The current rate of sea-level increase in the Caribbean and Gulf of Mexico is about 3.9 inches (10 cm) per 100 years. In the Pacific, the absolute sea level is also rising. However, long-term changes in sea level relative to land vary considerably within the main Hawaiian Islands and some of the South Pacific islands due to geologic uplift and subsidence. Trends in relative sea level thus vary greatly from island to island, such that there is no discernible long-term average trend for sea-level rise for the Pacific islands as a group. There is also extreme variability in relative sea level associated with transient events such as ENSO, storm surges, and extreme lunar tides.

Climate of the Coming Century

The Hadley, Canadian, and other global climate models suggest it is possible that the Pacific and Caribbean islands will be affected by: changes in patterns of natural climate variability (such as El Niño); changes in the frequency, intensity, and tracks of tropical cyclones (hurricanes and typhoons); and changes in patterns of ocean circulation. These islands are also very likely to experience increased ocean temperatures and changes in sea level (including storm surges and sustained rise).

For the Caribbean and the Pacific, both of the primary models used in this Assessment project increasing air and water temperatures. For the Caribbean, both models project slightly wetter conditions in winter, while the Hadley model suggests slightly drier conditions in summer and the Canadian model suggests that in summer parts of the Caribbean will be wetter and parts drier. For the Pacific, both models show greater warming in the central and eastern equatorial Pacific and an attendant eastward shift of precipitation.

Any changes in ENSO patterns would affect precipitation, sea level, and the formation and behavior of cyclones (typhoons and hurricanes), with consequences for both the Caribbean and Pacific islands.

Key Findings

- Islands are uniquely vulnerable to many of the potential impacts of climate change: changes in hydrologic cycles;temperature increases;and sea-level fluctuations.
- On many islands, water resources are already limited. Water supplies could be adversely affected by changes in hydrologic cycles that result in more frequent droughts and/or floods and changes in sea level that result in saltwater intrusion into freshwater lenses.
- In Puerto Rico,the US Virgin Islands,and mountain islands of the Pacific, climate changes that result in increased extreme precipitation events are of particular concern since flooding and landslides often result from such extreme events today. Model scenarios frequently project increases in rainfall intensity as global temperatures rise.
- Both coastal and inland island populations and infrastructure are already at risk from climate extremes. Model projections suggest that the islands could possibly be affected by changes in patterns of natural variability in climate (such as El Niño) and changes in the frequency, intensity, and tracks of tropical cyclones (hurricanes and typhoons). Both the Pacific and Caribbean regions are familiar with severe cyclones,which have caused billions of dollars in damage from the destruction of housing, agriculture, roads and bridges,and lost tourism revenue. Any increases in frequency or intensity would have negative impacts on island ecosystems and economics.
- Islands are home to rare ecosystems such as tropical forests,mangrove swamps,coral reefs, and seagrass beds,with many unique and specialized endemic species (those that occur nowhere else). These resources are already threatened by invasive non-native plant and animal species,as well as from the impacts of tourism,urban expansion,and various industrial activities, giving the islands the highest rates of extinction of all regions of the US. Many of these ecosystems are also highly sensitive to changes in temperature and are likely to change or be destroyed by changes in climate. For example,coral reefs are sensitive to changes in water temperature,and increases in the frequency or severity of El Niño events could result in increased bleaching and possible die-off of corals.
- Other ecological concerns include increased extinction rates of mountain species that have limited opportunities for migration,and impacts on forests due to floods,droughts,or increased incidence of pests,pathogens,or fire. Any increase in the frequency or intensity of hurricanes could influence forest succession,and would generally favor invasive species. In addition,the unique cloud forests located on some of these islands occupy a narrow geographical and climatological niche that would be threatened by increases in temperature and changes in the hydrologic cycle.
- Episodic variation in sea level,and the associated erosion and inundation problems are already extremely important issues for many of the US-affiliated islands. Saltwater intrusion into freshwater lenses and coastal vegetation,and coastal erosion would only become greater problems should climate changes result in changes to normal weather patterns, changes in ocean circulation patterns,and increased sea-level rise.
- Tourism remains a significant contributor to the economies of many of these island jurisdictions. Should climate change in these regions negatively impact ecosystems or freshwater supplies, tourism would suffer. As has happened in the past,tourists are likely to select alternate destinations to avoid the impacts of climate changes and extreme weather events.
- For island communities to become more resilient to a changing climate they may consider implementing any number of adaptive strategies. Some of the strategies for the islands involve: increased use of climate forecasting capabilities for planning protection and mitigation measures; consideration of changing land use policies and building codes;use of improved technologies; increased monitoring,scientific research,and data collection;and improved management policies. In addition,broad public awareness campaigns and communication with user groups are important for improving public health and safety and protecting natural resources.

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE US-AFFILIATED ISLANDS OF THE PACIFIC AND CARIBBEAN

PHYSICAL SETTING AND UNIQUE ATTRIBUTES

This chapter deals with the US-affiliated islands of the Caribbean and Pacific. Included are:the Commonwealth of Puerto Rico (PR) and the US Virgin Islands (USVI) in the Caribbean:and the Hawaiian Islands,American Samoa,the Commonwealth of the Northern Mariana Islands (CNMI),Guam,the Federated States of Micronesia (FSM),the Republic of the Marshall Islands (RMI), and the Republic of Palau (RP) in the Pacific. The latter three are independent nations in free association with the United States;Hawaii became the 50th state of the US in 1959;the Virgin Islands,Guam,and American Samoa are US territories;and Puerto Rico and the Northern Mariana Islands are commonwealths.

Islands contain diverse and productive ecosystems, and include many specialized and unique species. Many islands are facing the stresses of rapid human population growth,increasing vulnerability to natural disasters,and degradation of natural resources. Droughts and floods are among the climate extremes of most concern as they affect the quality of water supplies in island communities and thus can have significant health consequences. Due to their small size and isolation,many islands face chronic water shortages and problems with liquid and solid waste disposal. Some are facing a species extinction crisis; for example,the Hawaiian Islands have the highest extinction rate of any state in the nation. Biological invasions and habitat loss seem to be the primary causes of the extinction crisis in Hawaii. For most island communities,infrastructure including,transportation aspects,and economic activities are concentrated near the coast,making them highly vulnerable to storm events and sea-level fluctuations.

The islands differ in geologic type,as well as by size, elevation,soil composition,drainage characteristics, and natural resources. There are barrier islands,continental islands,coral islands,and volcanic islands. Islands can also be of mixed type,such as continental islands with raised reefs or volcanic islands surrounded by coral reefs. Some low-lying coral islands or atolls rise only a few feet above sea level whereas some volcanic islands have mountains thousands of feet high. Island entities also may be single islands or groups of islands; for example,American Samoa consists of five volcanic islands and two coral atolls, whereas Guam is a single mountain island. The islands discussed here also vary considerably in terms of the types of human communities,their economic structure,and their lifestyles and infrastructure, ranging from large densely populated cities (e.g.,Honolulu,San Juan) to small villages,dispersed populations,and unpopulated islands (Rapaport, 1999;Lobban and Schefter, 1997;Low et al.,1998; Wiley and Vilella,1998;Loope,1998).

SOCIOECONOMIC CONTEXT

The islands of the Pacific and Caribbean are host to diverse communities,many of which are especially vulnerable to climate variability and change. While there are many commonalities among island communities,an appreciation of social,political,economic,and cultural diversity can help decision-makers involved in the planning of appropriate strategic responses to climatic perturbations.

American-affiliated islands in the Pacific and Caribbean share a common history of transition from indigenous to colonial and,most recently, to post-colonial society;but these histories have resulted in an array of political structures including US state,US territory, commonwealth,and freely associated state. Many of these islands have held special significance for US national security interests. On many islands,macro-scale political systems operate in conjunction with traditional sociopolitical structures. In some of the Pacific islands, for instance, the chief-based systems still influence political action,particularly at the local level. These diverse political organizations are instrumental in the planning and implementation of climate-related policies and programs.

The US-affiliated islands of the Pacific and Caribbean reflect considerable economic diversity which includes subsistence agriculture and fishing;

tourism;tuna processing and transshipment;and export-led agricultural production of crops such as sugar cane,bananas,pineapple,coffee,spices,and citrus fruits. In addition,some islands are developing the infrastructure to support high-tech telecommunications and computer industries. Some islands, such as CNMI and Puerto Rico,have established substantial manufacturing sectors. Despite this,many of the islands continue to depend on federal subsidies and military spending. While tourism, agriculture, fishing,and transshipment are common in most all the islands,the relative contribution of each sector to the overall economy varies from island to island, and most islands continue to rely on a mix of techno-industrial and subsistence strategies. Further, many island economies are intricately linked with wider economic structures and,as such,are especially vulnerable to fluctuations in the international market,which affect the prices of both imported and exported goods. Climate change and variability, whether through extreme events or gradual change, can potentially affect all island industries.

Culturally, the islands are remarkably diverse as well. Witness the strong Boriqua culture of Puerto Rico in the Caribbean,and the Samoan and Chamorro cultures of the Pacific. The Federated States of Micronesia is home to several different language and culture groups. Further, ethnic diversity is compounded by historical and contemporary migration patterns,which include not only internal migration of indigenous island peoples,but also some migration to and from the continental US and other countries. Growing manufacturing industries in the Commonwealth of the Northern Mariana Islands for instance,have attracted migrants from the Philippines,China,and Korea.

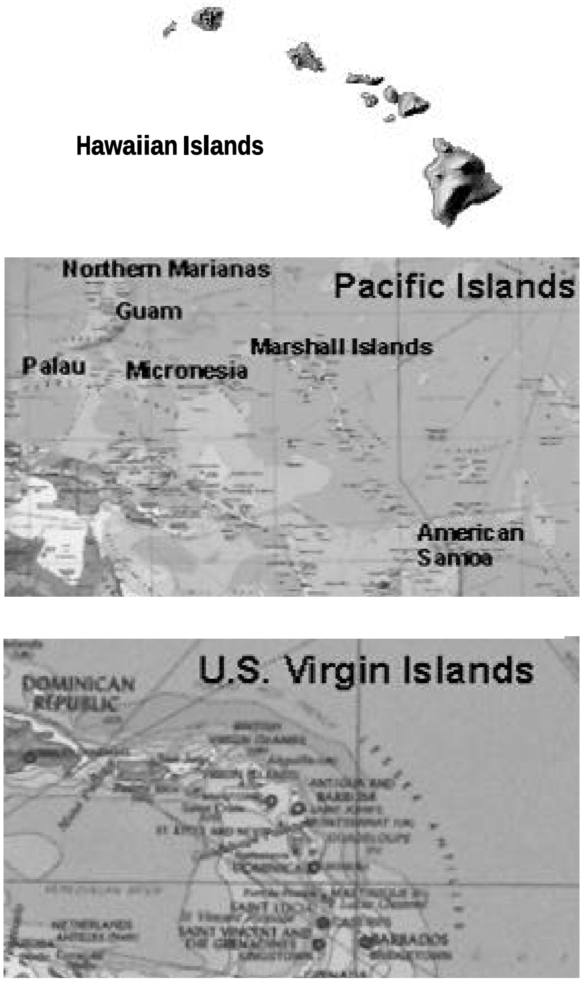

Figure 1: The scope of this section includes the US-affiliated islands of the Caribbean and Pacific. In the Caribbean, this includes Puerto Rico and the US Virgin Islands. In the Pacific, it includes the Hawaiian Islands, American Samoa, the Commonwealth of the Northern Mariana Islands, Guam, the Federated States of Micronesia, the Republic of the Marshall Islands, and the Republic of Palau.

Cultural values and belief systems can significantly influence people's responses to climate and climate changes as well as their responses to preventive or ameliorative policies and strategies. In many Pacific islands,land has inherent cultural value to the populations and therefore any potential threats are regarded as especially serious. Patterns of land ownership/tenure and resource use in many of the island jurisdictions addressed in this Assessment reflect a mix of traditional practices with strong and varying cultural roots combined with more recent policies that derived from periods of colonial occupations. In the Federated States of Micronesia, for example,land ownership remains the most valued right, reflecting the short supply and traditional importance of the land and the natural resources it supports (FSM National Communication,1999). In the traditional economy of the FSM,land is not a commodity to be sold or traded. While the states have legal authority over land for "eminent domain and condemnation," use of that power is strongly avoided (FSM National Communication,1999).

These complex patterns of land ownership create challenges for many climate change response (adaptation) options. The FSM National Communication to the United Nations Framework Convention on Climate Change (UNFCCC) notes, for example,that the relocation of a large proportion of the coastal population to elevated lands on high islands can only occur with the concurrence of the owners of those elevated lands and requires long-term land use planning accompanied by changes in traditional patterns of land tenure (FSM National Communication, 1999). The FSM National Communication to the

UNFCCC also highlights the fact that such challenges are even greater when considering off-island re-settlement in response to sea-level rise impacts on low-lying atolls. The FSM National Communication notes that pursuit of such an option would "have to be achieved without disruption to host communities and with sensitivity to and careful regard for the traditional values and practices of both the displaced and host communities"(FSM National Communication,1999).

Demographically, Pacific and Caribbean islands include densely populated urban centers such as Honolulu,Hawaii and San Juan,Puerto Rico to sparsely populated outer islands of the Federated States of Micronesia. Some of the highest population densities in the Pacific are found on Majuro and Ebeye in the Marshall Islands. While future population growth rates in the Caribbean appear to be attenuated,some Pacific island populations are growing rapidly. For example,from 1982 to 1998, the population of Majuro virtually doubled from about 15,000 to over 30,000. Pacific Islanders represent one of the fastest growing groups of migrants to the mainland United States. As the impact of climate change is felt more strongly, this trend is likely to continue.

ECOLOGICAL CONTEXT

The ecosystems of the islands discussed in this chapter can be characterized as tropical, rich in biological uniqueness,and susceptible to disturbance and biological invasions.[1] The isolation of islands has resulted in the evolution of unique floras and faunas with large numbers of endemic species — those found nowhere else on Earth (Low et al., 1998;Wiley and Vilella,1998;Loope,1998). Islands in both the Pacific and Caribbean are facing an extinction crisis as a result of steady habitat destruction,and competition and predation by introduced species. Small population sizes and lack of room for migration exacerbates the vulnerability of island species. The situation on many islands is becoming critical as the area of undisturbed natural habitat diminishes (Low et al.,1998;Wiley and Vilella,1998; Loope,1998). Fortunately, unique terrestrial and marine resources are still found in the tropical US on islands which have few or no human inhabitants such as Baker and Howland Islands, Jarvis Island,the Johnston Atoll,and the Kingman Reef among others (OIA,1999).

The Caribbean has a limited resource base, yet contains some of the most biologically productive and complex ecosystems found in the world. These include coral reefs,beaches,seagrass beds,mangrove forests,and coastal estuarine ecosystems. Native tropical rainforest (including mamey, sierra palm, and tree fern) and moist forest once dominated much of Puerto Rico,but much of this land has given way to cultivation,pasture,and other development. Drier areas support dry grasslands and cacti as well as forests of royal palm,acacia,and other tropical trees. Mangrove swamps dominate much of the coastline. The US Virgin islands are hilly due to their volcanic origin with land cover consisting primarily of cactus, grasses,and sparse tropical woodland and shrubland. Some native vegetation has been lost to stock grazing and the cultivation of fruit and vegetable crops and sugarcane.

The native vegetation cover of the Hawaiian islands includes tropical coastal and lowland shrublands, grasslands, wet forests,tropical montane rain forests, and shrublands (Loope,1998). Much of the coastal and lowland vegetation,and increasingly, the interior montane vegetation,have been lost to urban, recreational,and agricultural development (grazing,sugarcane,and pineapple plantations),and to introduced species.

American Samoa features rain forests in the interior mountains. Much of the coastal zone is under cultivation for coconut,taro,and other crops. Guam's principal land cover consists of tropical shrubland and limestone forest in the north and sword grass and dense jungles along river valleys in the volcanic south. The Marianas are not considered to be tropical rain forest. The flora consist of vines,shrubs, ferns,and grasses,including savanna and trees. The more common trees include:coconut, flame tree, Formosan koa,ironwood (Casuarina),banyan, papaya,tangan,mangrove and a few other varieties. In general,the variety of botanical species is limited on the CNMI and there are no vegetation zones (CNMI website,2000).

Over 97% of US coral reef resources are in the territorial waters of Hawaii and the US territories and commonwealths. Hawaii has the widest range of reef habitats among the islands discussed in this report,with a significant portion of US reefs in the northwest Hawaiian Islands. The US territories,commonwealths,and freely associated states,because of their location in tropical waters,have extensive reef habitats that are important culturally, economically, and biologically. For example,the abundant and wide variety of sea life within CNMI waters includes

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[1] This section outlines information on current island ecosystems and biodiversity. The VEMAP modeling system providing information about potential future changes to vegetation and ecosystems was not run for the islands as it was for the conterminous US.

US Affiliated Islands of the Caribbean and Pacific

Name/ US Affiliation	Geologic Type	Location/Description	Current Population (Approx.)	Major Economic Sectors
Commonwealth of Puerto Rico	One volcanic island composed of uplifted sedimentary rocks.	• Located SE of Miami on the northern edge of the archipelago of islands on the Caribbean plate. • 3,425 sq mi;8,871 sq km • Abundant rain in the North;dry climate in the South.	4 million.	Manufacturing Services Government Agriculture Tourism
US Virgin Islands Territory	Three volcanic islands (St. Croix,St. John,and St.Thomas) composed of uplifted sedimentary rocks.	• Located 1,000 miles SE of Miami on the northern edge of the archipelago of islands on the Caribbean plate. • 133 sq.mi.;344 sq.km • No lakes, rivers or streams.	120,000	Tourism Government
Hawaiian Islands State	Eight volcanic islands (Kauai, Oahu,Molokai,Lanai,Maui, Kahoolawe,Niihau and Hawaii). Also consists of NW Hawaiian Islands and Johnston Atoll.	• Located 2,400 miles SW of California and on the Tropic of Cancer • 6,450 sq.mi.;16,706 sq.km. • Sea area:833,171 sq.mi. • Majority of US coral reefs.	1.2 million	Tourism Agriculture Military spending Manufacturing Government
American Samoa Territory	Five volcanic islands and two coral atolls (Ofu, Ta'u,Swains Island,Tutuila,Olosega,Rose Island,and Aunu'u)	• Located 2,700 miles NE Australia • 76 sq.mi.;197 sq.km. • Rainforests in interior; mountainous regions	60,000	U.S. federal expenditures Canning industry Small tourism industry Government
Commonwealth of the Northern Mariana Islands	Fourteen volcanic islands	• Located at the edge of the Philippine plate. • 185 sq.mi.;479 sq.km. • Formed by underwater volcanoes along Mariana Trench.	66,000	Tourism Garment manufacturing Government Fish transshipment
Republic of the Marshall Islands Freely Associated State	29 coral atolls (each made up of many islets) and 5 low-lying volcanic islands	• Located about 2,136 miles SW of Hawaii • 70 sq.mi.;181 sq.km. • Each atoll is a cluster of many small islands encircling a lagoon • None of these islands is more than a few meters above sea level.	60,000	US aid Tourism Fisheries Subsistence Agriculture Craft items (wood carvings, shell and woven baskets)
Republic of Palau Freely Associated State	Several hundred volcanic islands and a few coral atolls (only 8 of the islands are inhabited).	• Located in the North Pacific Ocean,SE of the Philippines. • 192 sq.mi.;497 sq.km. • The 8 islands that are inhabited include Kayangel Island, Babelthaup,Urukthapel, Koror, Peleliu,Eli Malk,Angaur, Sonsoral and Tobi.	17,000	Tourism Craft items (wood,shell pearl) Commercial fishing Agriculture (subsistence) Government
Federated States of Micronesia Freely Associated State	A group of 607 small islands consisting of volcanic islands and coral atolls.	• Located in the Western Pacific about 2,500 miles SW of Hawaii. • 271 sq.mi.;702 sq.km • 4 states:Chuuk, Pohnpei, Yap and Kosrae.	127,000	Tuna fishing Tourism Government Subsistence Craft items (wood carvings, shell and woven baskets)
Guam Territory	One volcanic island composed of uplifted sedimentary rocks.	• Guam is the largest Micronesian Island. • 209 sq.mi.;541 sq. km. • Formed by the union of two volcanoes,northern Guam is a flat limestone plateau while the southern part is mountainous.	150,000	Tourism Military/government Tuna and other cargo transshipment Airline hub

coral gardens that harbor myriad mollusks,plant life, and tropical fish. The near-shore reef and lagoon areas are important for subsistence fishing,particularly net throwing. Many sea cucumbers occur in the shallow lagoon waters (CNMI website,2000).

The Freely Associated States contain a wide range of terrestrial and marine habitats,such as coral reefs and mangrove forests. The Exclusive Economic Zone of the Federated States of Micronesia (FSM) covers over one million square miles (2.6 million sq. km) of ocean and contains the world's most productive tuna fishing grounds. The estimated market value of tuna caught within FSM waters is valued at over $200 million per year. Pohnpei State,the location of the FSM's capital, receives an average of over 180 inches of rain per year and is covered by lush rainforests,and surrounded on the southern side with some of the most extensive mangrove wetlands in the Pacific Islands region. The rock islands in the Republic of Palau are uplifted fossil coral reefs that have been rounded by erosion. Coral reef ecosystems in Palau,which suffered from extensive bleaching during the 1997-1998 El Niño,are regarded as among the best diving areas in the world.

Unique terrestrial and marine resources of the tropical US are found in insular areas in the Pacific which have few, if any human inhabitants. These include Baker and Howland islands which are national wildlife refuges (Howland:birds and marine life; Baker:marine life). Jarvis Island,another national wildlife refuge,serves as habitat for seabirds and shorebirds. Johnston Atoll is home to 194 species of inshore fishes and sea turtles,and is a site for roosting and nesting of 500,000 seabirds. Kingman Reef has a rich marine fauna and the Northwest Hawaiian Islands National Wildlife Refuge includes over 100 islands with an estimated 616,000 pairs of Laysan albatrosses and 21 other species of seabirds (Low et al.,1998;Harrison,1990). The CNMI islands of Asuncion,Guguan,Maug,Managaha,Sarigan,and Uracas (Farallon De Pajaros) are maintained as uninhabited places. No permanent structures may be built and no persons may live on the islands except as necessary for the purposes for which the islands are preserved. The islands are preserved as habitats for birds, fish,wildlife,and plants. The three islands that are collectively known as Maug have been given permanent status as wildlife preserves (CNMI website,2000).

CLIMATE VARIABILITY AND CHANGE

The islands of the Pacific and Caribbean experience relatively high air temperatures and low seasonal variations in air temperature throughout the year compared to most of the US mainland. However, other climate variables exhibit distinct seasonal patterns,particularly rainfall distribution,which results in wet and dry seasons. For example,precipitation patterns differ greatly over the Pacific,with a pronounced winter rainfall maximum in Hawaii and a late-summer/early fall maximum in Guam. In the Caribbean,the wet season is during the summer. In the Pacific,tropical storms and typhoons are common between May and December, although intense tropical cyclones can affect Guam and the CNMI during any month of the year. In the Caribbean,the hurricane season extends from June to November.

In addition to the seasonal variations,there are strong year-to-year fluctuations. For example,the El Niño/Southern Oscillation (ENSO) causes fluctuations in sea level, rainfall,and cyclone activity (hurricanes or typhoons,depending on the region) in both the Pacific and Caribbean islands. In the Caribbean,Atlantic hurricanes are suppressed during El Niño events,while their numbers increase during La Niña events. In the Pacific,during El Niño events,Hawaii,Micronesia,and the islands of the southwest tropical Pacific often receive below normal rainfall. Despite this,El Niño can also increase the risk of intense tropical cyclones for Hawaii,American Samoa,and the eastern half of Micronesia. Additionally, areas of above normal precipitation,along with greater tropical cyclone activity, typically shift eastward towards French Polynesia. During La Niña events,parts of Micronesia can receive very heavy rainfall during what is normally their dry season.

Observed Climate Trends

Over the past century, average annual air temperatures in the Caribbean islands have increased by more than 1°F (0.5 °C),while average annual air temperatures in the Pacific Islands have increased by about half this amount. Globally, sea level has risen by 4 to 8 inches (10-20 cm) in the past 100 years but with significant local variation. Relative sea level, which takes into account natural or human-caused changes in the land elevation such as tectonic uplifting and land subsidence (sinking),is showing an upward trend at sites monitored in the Caribbean and Gulf of Mexico. The current rate of relative sea-level increase in the Caribbean and Gulf of Mexico is about 3.9 inches (10 cm) per 100 years. While absolute sea level is also rising in the Pacific, geologic uplift is exceeding or keeping pace on many islands. As a result,across the set of islands,there is no consistent sea-level trend for the Pacific. Although showing no average net rise, relative sea level fluctuates widely, due to effects such as the ENSO cycle.

The highest frequency of cyclones in the Caribbean occurs in the western Bahamas and along the US eastern seaboard and adjacent Atlantic Ocean. There has been considerable decadal variability of hurricanes during this century (see Reading,1990;Diaz and Pulwarty, 1997;Landsea et al.,1995). Among other factors,decadal variability is affected by ENSO as well as changes in the thermohaline circulation (THC),the large-scale oceanic circulation in the Atlantic that includes the Gulf Stream. For example, Gray et al.(1997),show that a weakening of the THC in the latter half of this century resulted in cooling of the Atlantic Ocean along the coast of northwest Africa,an increase in the low-level pressure gradient between this region and the central Sahel,and a resulting reduction in the strength of the easterly waves that originate off the coast of Africa and propagate into the tropical Atlantic. These easterly waves are responsible for hurricane activity in the Caribbean. Therefore, changes in THC help regulate hurricane occurrence in the Atlantic.

Hurricane activity in the western Atlantic is reduced during the season following the onset of an El Niño event in the Pacific. The reason for El Niño occurrence leading to decreased incidence of hurricanes is because of the presence of anomalously strong westerly winds in the upper troposphere over the Caribbean and equatorial Atlantic (Gray, 1984). The strengthened winds result from extra-deep cumulus convection in the eastern Pacific Ocean that occurs during El Niño events. Hurricanes in the Atlantic tend to return to normal in the second summer following such an event. In spite of the relationship between hurricanes and El Niño events,there is little net effect on the precipitation in the region.

Scenarios for Future Climate

Model projections suggest it is possible that the Pacific and Caribbean islands will be affected by: changes in patterns of natural climate variability (such as El Niño); changes in the frequency, intensity, and tracks of tropical cyclones (hurricanes and typhoons);and changes in patterns of ocean circulation. These islands are also very likely to experience

The El Niño/Southern Oscillation (ENSO) Phenomenon

The term "El Niño" refers to the warm phase of the ENSO cycle when ocean temperatures in the central and eastern tropical Pacific tend to increase. The term "La Niña" refers to a phase of the ENSO cycle when waters in the central and eastern Pacific tend to be cooler. The ENSO cycle,normally about one year in duration,is a continuously evolving pattern of ocean-atmosphere behavior and represents one of the dominant patterns of natural variability in the climate system worldwide. Its frequency of occurrence is approximately every 2 - 7 years.

El Niño is thus one phase of the ocean half of a coupled ocean-atmosphere phenomena in the tropical Pacific (see Pielke and Landsea,1999). Its atmospheric partner is known as the Southern Oscillation,a periodic oscillation of atmospheric pressure between the western and eastern Pacific Ocean. Under normal,non-El Niño conditions,atmospheric pressure is lower over the western Pacific and higher over the eastern Pacific. This pressure gradient helps drive the (surface) trade winds from east to west or from high pressure to low pressure and results in a tendency to maintain higher sea levels in the western Pacific Ocean than in the east. During an El Niño event,the atmospheric pressure gradient lessens, resulting in surface winds that diminish or, sometimes, reverse direction. The see-saw in atmospheric pressure,coupled with the eastward movement of warm water, results in a drop in sea level in the western Pacific Ocean and a migration of higher than normal sea-level conditions to the east (along with the warm water due to reduced upwelling). In fact,this eastward migration of sea level is one of the observational signals that an El Niño event is underway. Images of El Niño events from satellites like TOPEX-POSEIDON show these changes in sea level as changes in the height of the ocean's surface. When this occurs,islands in the far western Pacific experience lower sea level while those in the central and eastern Pacific experience a transient increase in sea level.

El Niños and La Niñas as a Function of Observed and Projected Sea Surface Temperatures

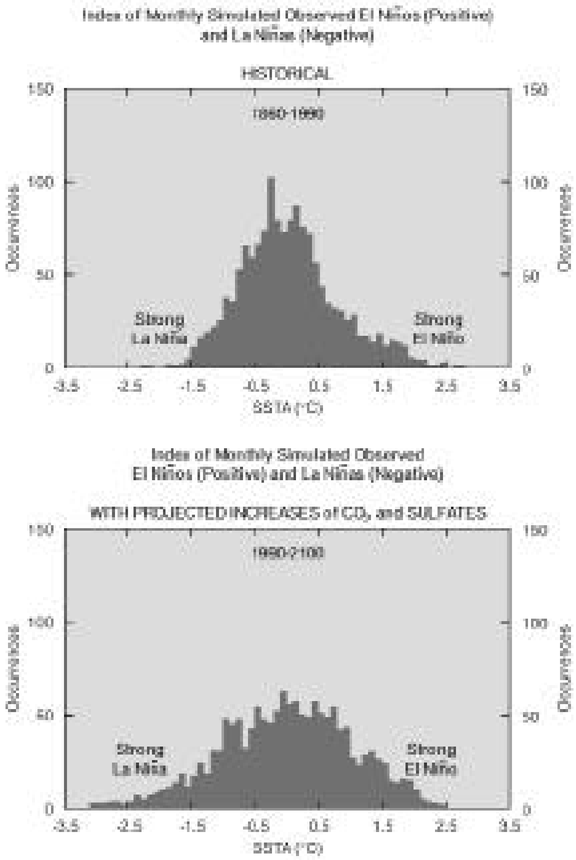

Figure 2. These model projections suggest stronger and more frequent El Niños and La Niñas as a result of climate change. Sea Surface temperature anomalies (SSTA) in the equatorial Pacific are used to measure the strength of El Niños and La Niñas. These model projections by the Max Planck Institute suggest a wider range of SST deviations from normal and thus more extreme El Niños and La Niñas in the future. The high bars in the center are occurrences of normal SSTs. In the projections in the bottom graph, these normal temperatures occur less frequently, while lower (La Niña) and higher (El Niño) SSTs occur more frequently. The Max Planck model is used here because it has been able to reproduce the strength of these events better than other models due to its physics and ability to resolve fine scale structure in the ocean. Source: Timmermann et al., 1999

increased ocean temperatures and changes in sea level (including storm surges and sustained rise).

For the Caribbean, most model simulations project increasing air and water temperatures, slightly wetter conditions in winter, and slightly drier conditions in summer. Models that suggest more persistent El Niño-like conditions across the Pacific imply a reduction in Atlantic hurricane frequency in the future. However, not all models concur on this point.

For the Pacific, the model simulations project a gradual increase of air and water temperatures. Some recent climate model studies also project that ENSO extremes are likely to increase with increasing greenhouse gas concentrations (Timmermann et al., 1999; Collins, 2000). Additionally, recent model results (Knutson and Manabe, 1998; Timmermann et al., 1999) have agreed with earlier studies (Meehl and Washington, 1996) in showing that as global temperatures rise due to increased greenhouse gases, the mean Pacific climate tends to more resemble an El Niño-like state, with greater relative surface warming in the equatorial eastern Pacific than the west. This implies a reduction of fresh water resources in areas of the western Pacific, Micronesia, and southwest tropical Pacific (Meehl, 1996). The existence of higher sea surface temperatures in the central and eastern Pacific could also result in an expansion in the area of the Pacific where tropical cyclones will form and migrate, as is the case during an El Niño. Other models show uniform warming across the Pacific or somewhat greater warming in the western equatorial Pacific.

Apart from the linkage with ENSO, there is significant uncertainty about how increasing global temperatures will affect hurricane or typhoon frequency and preferred tracks in both the Caribbean and the Pacific regions (see Landsea, et al., 1996; Henderson-Sellers, et al., 1998; Emanuel, 1997, 1999; Meehl, et al., 2000). Studying the effect of global warming at a time of doubled CO_2, Bengtsson et al. (1997) conclude that there are significantly fewer hurricanes (especially in the Southern Hemisphere), but no significant change in the spatial distribution of storms. The model used by Bengtsson, et al. (1997), however, was barely adequate to resolve tropical cyclones. More ocean surface warming could create more opportunity for storm development, given the right atmospheric conditions. Other results, using a nested high-resolution model (resolution of up to 1/6 degree or 18 km) indicate a 5-11% increase in surface winds and a 28% increase in near-storm precipitation (Knutson et al., 1998; Knutson and Tuleya, 2000). Another recent overall assessment regarding changes in hurricane strength suggests a 5-10% increase in tropical storm wind speed by the end of the 21st century (Henderson-Sellers, et al., 1998).

It is also a fact, however, that until capabilities are more developed for accurately simulating ENSO and changes in the thermohaline circulation in global climate models, the possibility of significant changes in the expected frequency, intensity, and duration of ENSO as well as tropical storms cannot be ruled out. It is even conceivable that changes in the strength of monsoon circulations in the South Pacific could have unanticipated effects on ENSO and related tropical storm frequency, paths,and strength.

KEY ISSUES

Two regional workshops were held to identify stakeholders'concerns regarding climate change and climate variability in the context of other current stresses for island and coastal environments and communities. The first workshop was held in Honolulu, Hawaii in March 1998,and participants identified issues of importance to the US-affiliated islands in the Pacific. The second workshop took place in July 1998 and addressed concerns of the south Atlantic coast of the US and the US-affiliated Caribbean islands. This chapter is based on presentations and discussions at these workshops, extant literature,and ongoing research into the consequences of climate variability and change to islands.

While the workshop participants identified numerous issues for consideration, four of the critical climate-related issues for the islands now and in the future include:

- ensuring adequate freshwater supplies
- protecting public safety and infrastructure from climate extremes
- protecting rare and unique ecosystems
- responding to sea-level fluctuations.

It should be noted that participants at the regional workshops did not identify long-term sea-level rise as the highest priority issue, focusing instead on water resource issues and storm impacts. There is a sense that the nature of the sea level issue for islands has been somewhat misunderstood in discussions of climate change. It is important to recognize that episodic variations in sea-level (like those associated with the ENSO cycle in the Pacific) and storm surges are already extremely important issues. In addition to considering only the consequences of a gradual,long-term rise in sea level,island communities will continue to face the consequences of episodic events (e.g., extreme lunar tides,ENSO related changes,and storm-related wave conditions) some of which themselves will be affected by climate change. Importantly, changes in sea level associated with natural variability exceed long-term projections of sea-level rise in some jurisdictions.

Many of the projected consequences of long-term sea-level rise,such as salt water intrusion into freshwater lenses and coastal erosion are already problems in some if not most island jurisdictions. According to USGS (1999a), for example, about 25% of the sand beaches on Oahu,Hawaii have been lost or severely degraded during the last 60 years. Climate-related changes of these conditions are seen,therefore,as magnifying existing problems rather than as problems in isolation from other stresses. Island communities must deal with these problems today and,in so doing,can develop important insights into how they might most effectively respond to climate-related changes in sea level over both the short- and long-term. Because the communities will act to mitigate the increased climate change problems periodically, they will not be adjusting to 100 years of climate change effects at one time,but rather to smaller effects more frequently during the century. This allows for staggered adaptation.

1. Freshwater Resources

The availability of freshwater resources is already a problem for island communities,as a result of their unique geography and the growth of population, tourism,and urban centers. Many islands suffer from frequent droughts and chronic water scarcity due to lack of adequate precipitation. In other cases, rainfall is abundant but access to freshwater is limited by lack of adequate storage facilities and delivery systems,or a geographic mismatch between the source and the site of the need. For the Pacific Islands,both a present and future key issue is drought or water scarcity conditions. For the Caribbean,drought is also a problem,but floods and landslides associated with hurricanes and heavy rainfall are an important addition to this region's list of key water-related issues. According to Larsen and Torres-Sanchez (1998) rainfall-triggered landslides are the most common type of landslide in the central mountains and foothills of Puerto Rico.

Future climate changes in the islands regions could include: changes in natural variability in weather patterns,ocean temperature,and currents (e.g.,patterns of El Niño); changes in the frequency, intensity, and tracks of tropical cyclones (hurricanes and typhoons) and their resulting precipitation;and/or changes in sea level. Any of these changes would impact the amount,timing,or availability of freshwater, such that freshwater issues will be increasingly serious concerns for the US affiliated Islands.

On the islands,demands for water are from multiple sources including agriculture,industry (including fish processing),households,and natural ecosys-

Freshwater Lens Effect in Island Hydrology

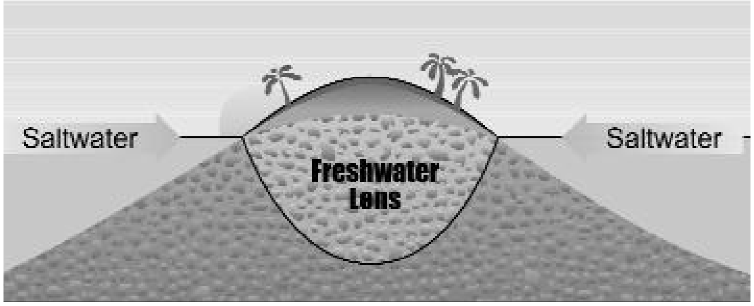

Figure 3. On many islands, the underground pool of freshwater that takes the shape of a lens is a critical water source. The freshwater lens floats atop salt water. If sea level increases, and/or if the lens becomes depleted because of excess withdrawals, salt water from the sea can intrude, making the water unsuitable for many uses. The size of the lens is directly related to the size of the island: larger islands have lenses that are less vulnerable to tidal mixing and have enough storage for withdrawals. Smaller island freshwater lenses shrink during prolonged periods of low rainfall, and water quality is easily impaired by mixing with salt water. Short and light rainfall contributes little to recharge of these sources. Long periods of rainfall are needed to provide adequate recharge. Source: Illustration by Melody Warford.

tems. Tourism is extremely water-intensive and is a major industry for the Commonwealth of the Northern Mariana Islands, Guam, Hawaii, Palau, Puerto Rico, and the Virgin Islands. Tourism development continues in these areas and the Federated States of Micronesia, the Republic of the Marshall Islands, and American Samoa all see tourism as one of their best options for economic development.

Many island communities rely upon groundwater resources called freshwater lenses. The size of the groundwater lens is directly related to the size of the island as well as incident rainfall, island recharge characteristics (controlled by land cover, evaporation, and geology), and the lateral leaking of lens water into the ocean. Larger islands have larger lenses and are more buffered from drought conditions while smaller islands have no lenses or shallow lenses that easily become depleted or contaminated with salt water. During drought conditions, there is no recharge to the lens, and the fresh water is depleted rapidly, especially if consumption is high. Low sea levels associated with El Niño lower the water table even more, making it more difficult to access the water and easier to damage the fragile interface between the fresh water lens and the underlying salt water. Low-lying atolls rely heavily on rainwater collection and are therefore least buffered against drought conditions.

The geology of the island controls the amount, quality, and seasonal availability of the water supply. Islands that are continental or of old volcanic origin exhibit complex movement of groundwater through layers of rock or clay. New volcanic islands generally have more dynamic movement of water through tunnels, holes, and layers of ash. Similarly, islands made up of coral or sand are quite permeable, so the rainwater infiltrates very quickly. Water quality is also an issue: many volcanic islands have highly permeable rock, which increases the potential for groundwater contamination and in some Pacific islands contamination problems reduce the "capacity" of the system (USGS Hawaii State Fact Sheet, 1996). In addition, seawater can contaminate the freshwater lens with salt if sea level rises, the lens is depleted, or the delicate freshwater-saltwater interface is damaged by excessive extraction.

Patterns of precipitation are important in determining whether islands have an adequate freshwater supply. Long periods of rainfall are needed to recharge the freshwater lenses since short and light rainfall tends not to contribute to aquifer recharge. Land use is an important determinant of infiltration; how much water infiltrates into the ground or flows into rivers and streams depends upon the land cover that catches the rain. If the land is covered by forest, the forest holds the rainwater for drier periods, but if the forest has been displaced by urban development, for example, the rain runs off faster leaving less for use during dry conditions. On some islands, destruction of forest cover has caused many formerly perennial streams to stop flowing in the dry seasons and has contributed to landslides during periods of heavy rain.

Pacific Islands. Rainfall, stream flow, and groundwater are fairly abundant on the big island of Hawaii, but many areas are withdrawing water at rates close to the estimated yield of aquifers near the populated areas (USGS Hawaii Fact Sheet, 1999a). Water use in many of the other Pacific Islands is now near the limit of the known freshwater resources, and demand exceeds the existing supply on many islands. In some cases, the problem is not the lack of adequate rainfall, but distribution, storage, and maintenance. Guam and the island of Hawaii are examples of the distribution problem due to their "geographic mismatch" between supply and demand. For example, the "Hilo side" of the big island of Hawaii consistently receives abundant rainfall and is one of the wettest places in the Hawaiian Islands, while the "Kona side" is where the majority of tourism development is occurring and has experienced significant periods of drought. Other islands,that more easily access their adequate rainfall, face storage,distribution,and maintenance problems. Pohnpei normally has an abundance of water, including waterfalls, springs,and rivers in the central areas. However, the island lacks storage and distribution systems,causing severe impacts under drought conditions.

Water system development in American Samoa, Guam,and Hawaii has thus far kept pace with growth and almost all residents have access to reliable supplies of quality water. On Saipan,the Commonwealth Utilities Corporation has struggled for decades to make improvements in an inadequate water distribution system and to keep pace with population growth and tourism development. On Pohnpei,despite its abundant rainfall,the public water system in Kolonia,the largest town,cannot provide an adequate supply of quality water to residents under "normal"circumstances. In rural areas, people take water directly from rivers and streams, many of which dry up during severe droughts,and while groundwater is available,there is often no system to access it. In the outer islands of the Marshall Islands and Federated States of Micronesia, residents rely on small rooftop catchment systems with only a few thousand gallons of storage capacity. On Majuro, the public water system is fed primarily from the international airport runway and that system has been supplemented by wells on Laura Islet,some 17 miles from the storage system at the airport. Colonia,Yap (FSM) depends on a small reservoir for water, but the reservoir, even if full at the beginning of a severe drought,dries up.

Currently the Pacific Islands experience drought conditions every two to six years,usually associated with the El Niño/Southern Oscillation (ENSO) cycle. The most extreme droughts appear to be associated with very strong El Niño events like those that occurred in 1982-1983 and 1997-1998. Rainfall during the 1997-1998 event in some areas was well below normal for the period October 1997 through September 1998. In some months, rainfall was as low as 3% of normal. These low monthly totals meant trouble for islands relying on catchment systems.

The water resources for many of the Pacific Islands could be most adversely affected by any increase in El Niño or El Niño-like conditions. These increases could take many forms such as more frequent and/or severe El Niño events,medium-sized El Niños that persist for multi-year periods,or other conditions that diminish precipitation over these islands,such as the "El Niño-like conditions" hypothesized to result from increased ocean temperatures. Due to overlapping time-scales,these changes could result in almost chronic drought conditions for some islands in the Pacific. Such a sequence would not allow islands critical recovery time from one drought before another sets in,or would stress their emergency preparedness capabilities if they were faced with an additional natural disaster on top of any protracted drought condition. A secondary consequence is migration:if such enhanced drought conditions occur over wide regions of the tropical Pacific,atoll populations may migrate in significant numbers to high-island population centers with more stable freshwater resources (Meehl,1996).

The Caribbean. In Puerto Rico and the US Virgin Islands,high population densities and the conversion of tropical forest to other uses have affected hydrology and water resources. These changes have contributed to overuse of existing water supply (even with reduced per capita use due to conservation programs,USGS,1999b),in-filling of public-supply reservoirs with sediment,and contamination of groundwater and surface water (Zack and Larsen, 1993).In the US Virgin Islands,and to a lesser extent in Puerto Rico,leaky septic tanks and inadequate sewage treatment facilities have degraded the quality of near-surface groundwater supplies (Zack and Larsen,1993). In addition,both Puerto Rico and the US Virgin Islands experience flash flooding and landslides that result from the combination of steep slopes and heavy rainfall typical of this region. Deforestation and development have contributed to increased flash flooding and landslide potential particularly under steep,denuded slopes. Poor drainage on floodplains has increased the vulnerability of these areas to various flooding events,while land-use patterns and inadequate construction increase the exposure of the population (Zack and Larsen,1993).

In the Caribbean,tropical storms/hurricanes are significant natural hazards,through the mechanisms of storm surge and high winds. In coastal locations of Puerto Rico and the US Virgin Islands,saltwater intrusion threatens the continued use of fresh groundwater and limits groundwater withdrawals.

Puerto Rico has abundant ground-and surface-water resources due to relatively heavy rainfall over the mountainous interior of the island and receptive, sedimentary rocks around the island's periphery (Zack and Larsen,1993). These form an extensive artesian aquifer system on the north coast. Water-table aquifers overlie the north coast artesian aquifer and occur along most of Puerto Rico's coastline. Artificial reservoirs on principal water courses col-

Responding to Drought in the Pacific Islands

The 1997-1998 El Niño event offers a vivid example of how forecasts and information about potential climate phenomena and their consequences can be used to support decision making and planning that benefit society. In September 1997,the Pacific ENSO Applications Center (PEAC) predicted a near-record drought for Micronesia,beginning in the November-December timeframe and ending in the May-June timeframe.

When severe drought was projected for the Northern Marianas (where there are not regular sources of good water at any time) beginning in February 1998,the government implemented a tightened water-rationing schedule. Each venue was assigned "water hours"of 2 - 4 hours each day. By February, El Niño had already reduced the island's rainfall level to 75% below normal,and the shortage was to continue for many months. The Commonwealth Utilities Corporation,the government entity responsible for the island's water system, also outlined a "severe drought scenario"in which commercial water users,such as hotels and garment factories, would be cut off from the island's water system for a few hours each day. A task force was established which pushed for legislation requiring every home and building to install a rainwater catchment system (this would,however, require loans or subsidies for low-income families).

For Majuro,PEAC provided a drought and typhoon forecast in September 1997 that indicated an increased typhoon risk and a sharp decline in rainfall beginning in December 1997. In November, the Government of the Republic of the Marshall Islands convened a task force to develop a drought response plan. Typhoon Paka struck the Marshall Islands in December 1997 and brought the last significant rainfall until June 1998. The government requested assistance from the US Commander-in-Chief, Pacific Command to repair pumps at the wells on Laura Islet. The water utility on Majuro developed a conservation plan,a public education program, and imposed water hours. At the height of the drought, residents of Majuro were getting 7 hours of water every 15 days. The Japanese government provided two 20,000 gallon per day (gpd) and one 16,000 gpd reverse osmosis (RO) units in February 1998. Following the US Presidential disaster declaration in March,six larger RO units were provided with funding from the US Federal Emergency Management Agency in April. In May 1998,the new pumps at Laura came on line and in June rainfall increased and the RO units were shut down.

The drought in Samoa was delayed until April because of its location in the Southern Hemisphere. For the Samoas,PEAC anticipated an increase in the risk of tropical cyclones and drought as a result of the El Niño. In April,May, and June of 1997, rainfall in Pago Pago was only 64% of normal. In July 1997,it was only 59% of normal. Their summer was closer to normal,but PEAC forecasted that rainfall for the period April through August 1998 would be well below normal and this was borne out. The American Samoa government organized a drought response that included such activities as establishing a drought task force and a public information campaign and has continued to rely on the PEAC and National Weather Service forecasts.

In May of 1998,American Samoa's single largest private employer, StarKist Samoa committed to implementing several in-house conservation

El Niño billboard used as a public information tool in the Pacific Islands - US National Weather Service, Pacific Region Office.

measures which would eventually reduce the canneries'daily water usage by 25%. The company had also utilized scenario-based planning,and acknowledged that the worst case would involve importing water from off-island by tanker in the amount of 50 million gallons.

Agriculture throughout the US-affiliated Pacific Islands during 1997-1998 suffered everywhere from the droughts, except on Guam. There, farmers used public water for irrigation,and the delay of heavy rains toward the end of the drought resulted in one of the most productive harvests in recent history. In the Commonwealth of the Northern Mariana Islands (CNMI),citrus and garden crops were most affected by the drought,and the hospital had to buy imported fruits and vegetables rather than rely on local suppliers. A limited damage assessment was done on Pohnpei and serious losses of both food and cash crops were sustained. Over half the banana trees evaluated had died or were considered seriously stressed. The loss of sakau (kava) was probably the most serious economic loss because it had become a major cash crop for Pohnpei. On Yap, taro losses were estimated at 50-65%,and betel nut prices increased more than 500%,although only 15-20% of the trees were lost. In Palau,imported food shipments increased from twice a month to once a week.Other climate-related consequences felt throughout the islands included changes in the migratory patterns of economically-significant fish stocks like tuna;stresses on coral reefs associated with increased water temperature; and increased sedimentation from erosion;and reduced local air quality in areas affected by wildfires. Guam, for example, experienced some 1400 fires and grass fire burned 20% of Pohnpei.

Relief food was supplied beginning in May 1998 to islands in the Marshalls and was also supplied to the outer islands of Pohnpei,Chuuk,and Yap. The Pohnpei Agriculture and Trade School,the US Natural Resources Conservation Service,and Pohnpei State Agriculture Department provided assistance to the farmers as the drought began to subside.Subsistence crops required 6-10 months for rejuvenation after the rains returned. The disaster management offices used PEAC and National Weather Service forecasts to plan food relief and replanting programs for the droughts in the Republic of the Marshall Islands (RMI) and the Federated States of Micronesia (FSM).

Overall,islands in the Pacific implemented many of the following measures when faced with drought conditions in 1997 and 1998:

- expanded public information and education efforts;
- continued emphasis on and funding for household rainwater collection systems;
- accelerated drought planning efforts;
- expanded drilling efforts and other activation of new water sources,such as the emergency use of monitoring wells to augment production;
- tightened pre-existing water restrictions and delivery scheduling schemes;
- more use of water-haulers to fill existing storage facilities;
- shifted farm location and range management (where livestock were pastured) to take advantage of more reliable, groundwater-based irrigation supplies;
- increased attention to water conservation, for example in concentrated leak detection and repair efforts;
- more extensive and effective use of ENSO forecast information;
- accelerated maintenance on water pumps and lines - acquired spare parts;and
- installed RO units.

Many of these improvements have long lasting positive effects – such as repair of pipes and pumps and increased storage capacity, alleviating the need for conservation until the next drought.

lect runoff and are used for water supply, flood control, and limited hydroelectric power generation. Ground water accounts for ~30% of the total amount of water used in Puerto Rico and surface water accounts for ~70% (Zack and Larsen, 1993).

The US Virgin Islands are much smaller and have a lower maximum elevation than Puerto Rico. These islands receive less rainfall and retain less fresh water. The US Virgin Islands have no perennial streams and only limited ground water resources. Retention dams have been used on ephemeral streams to promote recharge of coastal aquifers (Zack and Larsen, 1993). In the US Virgin Islands, 65% of drinking water supplies are provided by desalinated seawater, making it the most expensive publicly supplied water in the United States (Zack and Larsen, 1993). Another approximately 22% of the drinking water supply originates from groundwater and 13% from rooftop catchments.

Flooding is a critical issue for Puerto Rico and the US Virgin Islands due to the topography and rainfall patterns of the islands. In the US Virgin Islands, human infrastructure (including buildings and roads) has covered many of the ephemeral channels that allowed for infiltration. This not only diminishes water supply, but greatly increases flash flood hazard. In Puerto Rico, flash floods typically result from rainfall that is intense in the upper basins but sparse or nonexistent on the coast. These events can trigger hundreds of landslides, which are common in the mountainous areas of Puerto Rico where mean annual rainfall and the frequency of intense storms are high and hillslopes are steep. One effect of these landslides is adding sediment to river channels, which is carried into downstream reservoirs. Combined with other factors such as heavy rainstorms, urban development, and agricultural practices, this sediment reduces the storage capacity of major reservoirs, and diminishes their efficiency at reducing flood peaks (Zack and Larsen, 1993). Large quantities of sediment are also washed into the ocean, where it is deposited on the reefs and deteriorates reef health.

Droughts are frequent and severe in the US Virgin Islands. Any minor depletions in rainfall dramatically affect agriculture and require water rationing (Zack and Larsen, 1993). Droughts are infrequent in Puerto Rico. However, mandatory water rationing was implemented six times during the 1990s resulting in significant agricultural and other economic losses (Larsen, 2000). A drought in 1994-95 affected more than one million people who endured mandatory rationing for more than a year (Larsen, 2000). Although Puerto Rico had seen lower mean annual rainfall in previous decades, the population growth changed the nature of the needed response. Public works projects were initiated including a $60 million project to dredge the sediment from the Loiza reservoir and $350 million for a new aqueduct system to interconnect north coast water supply systems (Larsen, 2000). Diminished streamflow has also severely affected biotic communities and ecosystem processes in stream channels in Puerto Rico (Covich et al., 1998).

Adaptation Options

Strategies for providing adequate water resources under changing climate conditions for island communities vary. Options could include: improved rainfall catchment systems; improved storage and distribution systems; development of under-utilized or alternative sources; better management of supply and infrastructure; increased water conservation programs; construction of groundwater recharge basins for runoff; more effective use of ENSO forecast information; and application of new/improved technology, such as desalinization. It would also be useful for island communities to prepare water needs assessments for the future and prepare, test, and improve emergency/contingency plans for periods of water shortage.

For key sectors, strategies include integration of climate considerations and projections of sea-level rise into community planning, water management decision making, and tourism development. Accurate assessments of current water budgets are critical for effective management of water resources, especially on small, densely populated islands with limited storage capacity (Larsen and Concepcion, 1998). Strategies for potential flood conditions are considered in the next section.

2. Public Health and Safety

Both coastal and inland island populations and infrastructure are at risk from climate-related extreme events. As reported earlier, model projections suggest it is possible that the Pacific and Caribbean islands will be affected by: changes in patterns of natural climate variability (such as El Niño); changes in the frequency, intensity, and tracks of tropical cyclones (hurricanes and typhoons); and changes in ocean currents; and that these islands are very likely to experience increased ocean temperatures and changes in sea level (including storm surges and sustained rise). For the Caribbean, models indicate increasing air and water temperatures, slightly wetter conditions in winter,

Potential Consequences of Climate Extremes on Infrastructure and Human Health

Disruption of lifeline systems, including water supply, energy supply, waste management,and sanitation due to fluctuations in temperature and precipitation,as well as storm events. Medical services can also be disrupted during storm events;

Effects on people and public health, due to decreased water quality and sanitation,impact on agriculture and consequently nutrition,and ecological changes that may increase the risk of disease transmission,and direct impacts from severe storms;and

Damage or destruction of infrastructure, including housing,lifelines,transportation,economic,and industrial infrastructure due to storms, related storm surge,and sea-level rise.

and slightly drier conditions in summer. Some models project persistent El Niño-like conditions across the Pacific caused by increased ocean temperatures. This also suggests that Atlantic hurricanes may decrease in the future because of the relationship of reduced hurricane activity in the Atlantic following the season of El Niño event onset in the Pacific. Nevertheless,there seems to be little net effect on total precipitation in the region because rain clouds still form and rain still falls, even in the absence of hurricanes.

For the Pacific,models indicate a gradual warming of air and water temperatures with an accompanying eastward shift of precipitation. This would be somewhat similar to what happens during El Niño events,and while not exactly the same,it would likely cause changes in local rainfall patterns similar to those experienced during the El Niño phase of the ENSO cycle. While this is still uncertain,one result suggests precipitation amounts associated with tropical storms will likely increase by more than 25% on average (Knutson et.al,1998);other results suggest a 5-11% increase in surface winds and a 28% increase in near-storm precipitation (Knutson and Tuleya,et al.,2000).

Globally, sea level is projected to rise two to five times faster over the 21st century than over the 20th century as increased warming causes glacial melting and thermal expansion of ocean water. The US-affiliated islands would be affected by variations in sea level,such as storm surge associated with tropical storms,and fluctuations associated with El Niño events.

With these types of projected climate changes,many current stresses that islands face will be exacerbated. Storms can directly damage structures,interfere with the provision of services to communities, cause deaths,and increase disease transmission. In American Samoa, for example,the majority of existing roads are located along the shoreline and are extremely vulnerable to damage by wind driven waves. Each section of new or rehabilitated roadway construction must include the additional costs of sea walls, resulting in extremely expensive highway construction. However, without properly designed shore protection,American Samoa could lose a major portion of the shoreline,as well as the entire length of adjacent roadway (OIA,1999) to storm surge. Both the Pacific and Caribbean regions are familiar with severe hurricanes and tropical cyclones,which have caused billions of dollars in damage from the destruction of housing, agriculture, roads and bridges,and lost tourism revenue (Walker et al.,1991;Scatena and Larsen,1991).

The unique topography of Puerto Rico and the Virgin Islands makes them susceptible to floods and landslides usually resulting from the extreme precipitation associated with these storms. On most islands, much of the population,transportation and social infrastructure,and economic activity is located near the coast,leading to dense areas of vulnerability. Diaz and Pulwarty (1997) suggest that the societal impacts of hurricane activity are potentially more worrisome in the future because of several socioeconomic changes that have occurred during this century. Population increases put more people in the path of potential hurricane devastation. Since transportation infrastructure has not kept pace with this population increase,it takes longer to evacuate people (e.g.,Hurricane Floyd and East Coast evacuations), even though hurricane-forecasting ability has improved. Finally, the value of insured property at risk is increasing,so the ability of insurance companies to keep pace with potential damage is diminishing.

Estimated Damages for Hurricane Marilyn in the US Virgin Islands

Category of Damage	Estimated Costs
Sewage Treatment Facilities	$1,000,000
Roads and Bridges	1,000,000
Damage to Manufacturing	1,000,000
Agriculture	1,000,000
Water	3,000,000
Protective Measures	10,000,000
Debris Removal	18,000,000
Telephones	30,000,000
Electrical	70,000,000
Lost Employment	80,000,000
Public Buildings	210,000,000
Damage to Hotels	253,000,000
Lost Tourist Revenue	293,000,000
Private Housing	1,300,000,000
Total	2,271,000,000

Source: The Virgin Islands Natural Hazard Mitigation Plan,B. Potter et al.,1995.

Leatherman (2000) also suggests that impacts from extreme events on the human community are a function of complex interactions between meteorological phenomena and the environment,including infrastructure (e.g.,transportation and other parts of the built environment),land-use patterns,and social, political,and economic systems. He also asserts that any future increases in destructive meteorological events,as are suggested by some of the climate change scenarios,will negatively impact the islands economically as well as socially.

Severe Storms. Hurricanes and typhoons are among the most socially devastating natural disasters,affecting more people on a yearly basis than earthquakes. Cumulative losses are also greater for hurricanes than earthquakes (Leatherman,1998). Hurricanes and typhoons cause billions of dollars in losses due to destruction of transportation and other infrastructure,life,and property. Increases in population density, changes in age structure and population health, urban sprawl,insufficient transportation infrastructure,and human occupation of coastal and flood-prone areas have all increased the vulnerability of populations and the infrastructure they depend on to hurricanes and typhoons. Deforestation has increased the amount of runoff and erosion that result from precipitation events contributing to the negative impacts of severe storms. One of those negative impacts is the increased risk of some diseases (e.g., *leptospirosis* and other water-borne diseases) following floods caused by storms (even storms that are far less intense than hurricanes). For example,data collected in certain areas of Florida show that increased flow resulting from storms carries 1,000 times the normal concentration of fecal sanitary bacteria (Alvarez,1998).

The Caribbean's worst hurricane season since 1933 came in 1995. Hurricanes Luis and Marilyn hit the Virgin Islands in September 1995 (see table for specific damages from Hurricane Marilyn). Damage was greatest in St.Thomas. Every telephone pole and 80% of the homes and businesses were destroyed. It took eight weeks to get desalinization plants running. Every cistern was contaminated by salt water and there was no electricity and no hand pumps to get water out of cisterns. Critical facilities that were affected included hospitals,power and desalinization facilities,sewer systems, fire houses, police stations,public shelters,ports,communication systems,and docks. Notably, hospital roofs were destroyed;sewage distribution systems were disrupted,leading to surface water and marine bay contamination;and power and telephone distribution systems required months of repairs and curtailed service. The US Virgin Islands Bureau of Economic Research estimated the economic loss at $3 billion. (Potter et al.,1995;National Hurricane Center, 2000).

The Pacific Islands have also suffered from severe storms. According to Pielke (2000),between the years 1957 and 1995,Hawaii suffered over $2.4 billion in hurricane damages. For the Pacific islands, 1992 and 1997 were particularly active years. In 1992 FEMA responded to "major disasters"in the Marshall Islands and Micronesia after Typhoon Axel

Hurricane Georges of 1998: Effects on Puerto Rico

On September 15,1998,a tropical weather system off the coast of West Africa was upgraded to a tropical depression. Within 24 hours,the tropical depression intensified to be the tropical storm that would become the fourth hurricane of the 1998 season,Hurricane Georges. At its strongest,Hurricane Georges had sustained winds of 150 mph,becoming a category 4 hurricane,the second most intense level of hurricane on the five-level scale used to measure intensity.

On September 21,Hurricane Georges (reduced to a category 3) began to sweep across Puerto Rico. It was to be the first hurricane since the 1932 San Ciprian hurricane to cross the entire island. The eye of the hurricane,measuring 25-30 miles wide,passed within an estimated 15 miles of San Juan,Puerto Rico’s capital,leaving a trail of devastation in its wake.

While rainfall across the island varied greatly, some areas received up to 26 inches of rain within a twenty-four hour period. The rainfall resulted in flooding,landslides,and catastrophic losses in infrastructure. Twelve people on the island of Puerto Rico were killed;three as a direct result of the storm,and nine others as an indirect result. Infrastructure impacts were enormous. The island lost 75% of water and sewage service,96% of electrical power, and suffered damage to 50% of utility poles and cables. An estimated 33,100 homes were destroyed. Road damage was estimated at $22 million and damage to public schools was estimated at $20-25 million. Agricultural damages were also significant with 75% of the coffee crop,95% of the plantain and banana crops,and 65% of all poultry destroyed (USGS,1999;NOAA,1999).

Overall costs to the US mainland and island territories reached $5.9 billion,with an estimated $2 billion or more in Puerto Rico alone. On October 15,1998,the Red Cross announced that Hurricane Georges had in fact been “the most expensive disaster relief effort in the organization’s 117-year history.” They estimate that solely within the US mainland and island territories, about 187,300 families were affected (American Red Cross,1998,1999).

struck in March;then in Guam in the aftermath of Typhoon Omar ($500 million dollars in damages). September 1992 saw Hurricane Iniki hit the Hawaiian island of Kauai. It resulted in 7 deaths,approximately $1.8 billion in damages,and $259.7 million in FEMA disaster relief costs. In December 1996, Typhoon Fern struck Yap and in April of 1997, Typhoon Isa struck Micronesia. Later that year, in December, Supertyphoon Paka ($650 million in damages) pummeled Guam and the Northern Marianas,as well as the Marshall Islands causing widespread destruction (Hamnett et al.,2000;FEMA website,2000).

Path of Hurricane Georges in Relation to Puerto Rico with Precipitation Totals

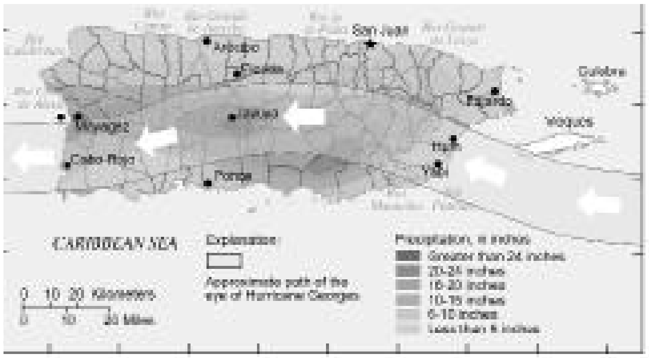

Figure 4. On September 21, 1998, Hurricane Georges swept across Puerto Rico. The eye of the hurricane was 25-30 miles wide and passed within 15 miles of the capital, San Juan, leaving a trail of devastation in its wake. The path of the hurricane and rainfall totals are shown here. Some areas received up to 26 inches of rain within 24 hours. Flooding, landslides, and catastrophic losses in infrastructure resulted. Hurricane Georges Map –USGS: http://water.usgs.gov/pubs/FS/FS-040-99/images/PR_fig01.gif *See Color Plate Appendix*

Landslides. Each year in Puerto Rico,landslides cause extensive damage to property and occasionally result in loss of life (Larsen and Torres-Sanchez,1998). Although landslides can be triggered by seismic activity and construction on hillslopes,the leading cause of landslides in Puerto Rico is intense and/or prolonged rainfall (Larsen and Simon,1993). Population density in Puerto Rico is high, about 1,036 people per square mile (400 people per square kilometer),and is increasing. This increase is accompanied by the use of less desirable construction sites. As a result,human populations are becoming more vulnerable to landslide hazards (Larsen and Torres Sanchez,1998). People tend to live in the coastal zone (vulnerable to storm surge),on flood plains,or on hillsides prone to landslides. In the meantime,human modifications are increasing the frequency of landslides. A study conducted in Puerto Rico in 1998 found that, although mean annual rainfall is high,intense storms are frequent,and hillslopes are steep, forested hillslopes are relatively stable as long as they are not modified by humans. However, the greater the modification of a hillslope from its original forested state,the greater the frequency of landslides (Larsen and Torres-Sanchez,1998).

Adaptation Options.
Strategies for improving public health and safety under changing climate conditions could include numerous options. For example:1) upgrading and protecting infrastructure (including transportation infrastructure);2) initiating comprehensive disaster management (and avoidance) programs (including mapping and risk analysis);3) changing and enforcing land use policies to avoid hazards/hazardous areas;4) adopting and enforcing increasingly stringent building codes;5) improving sanitation and health care infrastructure;6) improving emergency plans;and 7) increasing public and official information and outreach programs related to the range of historical disaster experiences and to future risks associated with climate change.

For potential flood conditions,adaptation measures include changes in land use policies that discourage construction in flood plains or areas at risk for landslides,and that allow for natural patterns of runoff. Improved monitoring,observation,alert, warning, and evacuation systems would also be desirable.

3. Island Ecosystems

Islands are extremely valuable as living laboratories for understanding species adaptation and evolution. Much as the Galapagos archipelago provided exceptional insight for Charles Darwin in the 1830s,the more ancient Hawaiian island chain has since become recognized as a premier site in the world for scientific studies of evolution in isolation. Before human influence,the Hawaiian Islands had no ants, reptiles,amphibians,or mammals (except for one bat species). The roughly 1,500 species of animals and plants that successfully colonized this climatically and topographically complex archipelago over thousands of miles of open ocean — on the winds, by floating,or attached to storm-driven birds (Carlquist,1980) — gave rise to roughly 15,000 species, over 90% of them endemic (found nowhere else).

Since the time of Darwin,it has been recognized that organisms of oceanic islands are notoriously vulnerable to extinction. Having been isolated for millions of years from the continual challenge of some of the selective forces that shape continental organisms,oceanic island fauna and flora are uniquely vulnerable to the human introduction of previously absent predators,diseases,and competitors (Loope and Mueller-Dombois,1989). Natural ecosystems also appear to be most vulnerable to many effects of climate changes (e.g.,temperature and carbon dioxide increases,precipitation changes, sea-level rise,and changes in the frequency and intensity of extreme events) since climatic conditions strongly determine where particular plants and animals can live, grow, and reproduce. Some species and ecosystems are so strongly influenced by the climate to which they are adapted,that they are very vulnerable to even modest climate changes. Some island ecosystems are already constrained by climate as well as geography and are likely to face extreme stress from projected climate changes while some species may disappear entirely. For example,increased ocean temperatures and possible changes in ocean circulation patterns will affect coastal ecological systems,such as mangrove forests and coral reefs and important marine resources such as fisheries. Often there is very little that can be done to assist ecosystems in adapting to the projected speed and amount of change.

Pacific Islands. The Hawaiian Islands are larger, have more topographical and climatic diversity, and have higher biological uniqueness than most other Pacific Islands. Hawaii also has the highest proportion of extinct and endangered species of anywhere in the US (USGS,1999a). Hawaii has lost over 70% of its original (pre-Polynesian) 140 land bird and 1200+ land snail species. Of 1,302 known taxa (89% endemic) in the Hawaiian vascular flora,106 (8%) are extinct and an additional 373 (28%) are considered at risk of becoming extinct in the near future. The “at risk”taxa include over 200 that are federally listed as endangered, roughly one-third of the total listed plants nationwide (Loope,1998). Loss of about two-thirds of the area of Hawaii’s natural habitats has been a primary reason for the losses to date; however, at present,biological invasions pose the greatest threats to further dismemberment of the biota.

Although invasive non-indigenous species are problematic throughout the Pacific,Hawaii,being in the mainstream of commerce,has suffered significantly (Holt,1998). Hawaii is inherently vulnerable to invasion due to great isolation from source areas of naturally colonizing species and high endemism (Mueller-Dombois and Fosberg,1998). This is not to say that other Pacific Islands have not suffered devastation by humans and their invasive species introductions. For example,Steadman (1995) estimates that more than 2,000 bird species may have been eliminated by early human settlers in Polynesia. The example of the brown-tree snake (*Boiga irregularis*) on Guam (Fritts and Rodda,1995) should serve as a cautionary note for all oceanic islands that non-indigenous species may explode in island habitats with unexpected consequences. According to Fritts (1999),the brown tree snake probably arrived on Guam via ship cargo from the New Guinea area and the first inland sighting was in the early 1950s. Some forested areas now have populations up to 13,000 snakes per square mile. The brown tree snake is responsible for essentially wiping out the native forest birds of Guam. Twelve species of endemic birds have disappeared from the island,and several others survive in such low numbers that they are close to extinction. The snake is responsible for economic impacts as well. For example,snakes crawling on electrical lines frequently cause power outages. More than 1,200 power outages have been attributed to snakes since 1978. The power interruptions have reportedly resulted in numerous problems ranging from food spoilage to computer failures and all include significant expenses for the population.

A comparable botanical example of the unintended consequences of non-indigenous species invasions and impact is seen in the invasion of the South American tree *Miconia calvescens* in Tahiti (Loope, 2000). *Miconia* now dominates 65% of Tahiti's forest canopy and its presence threatens some 40-50 endemic plant species to the point they are now on the verge of extinction (Meyer and Florence,1997). *Miconia* is a serious issue in Hawaii as well. Probably because of its attractive purple and green foliage,it was introduced to Hawaii as an ornamental — a single tree in the Oahu Wahiawa Botanical Garden in early 1960. By 1964,it had reached Hawaii and by the late 1960s or early 1970s it had reached Maui. Based on a 1995 discovery of a fruiting tree over 10 meters tall,it is estimated that it reached Kauai by the early 1980s. Its presence in Hawaii poses a threat to endemic plant species in habitats receiving 1800-2000 mm (75-80 inches) or more of annual precipitation (Loope,2000). The vulnerability of oceanic islands to invasions cannot be underestimated.

The USGS (2000) Hawaiian Ecosystems at Risk (HEAR) project asserts that "the silent invasion of Hawaii by insects,disease organisms,snakes, weeds, and other pests is the single greatest threat to Hawaii's economy and natural environment and to the health and lifestyle of Hawaii's people." According to HEAR,millions of dollars in crop losses,the extinction of native species,the destruction of native forests,and the spread of disease can already be attributed to alien pest (plant and animal) invasions,with many more harmful pests now threatening to invade Hawaii and cause further damage. For example,an invasion of ant species such as the "red imported fire ant" *(Solenopis invicta)* and the little fire ant *(Wasmannia auropunctata)* may pose a threat to Pacific islands'biodiversity, tourism, agriculture,and quality of life that rivals the threat of global climate change (R.Thaman,University of the South Pacific,personal communication,1999).

In spite of profound human modification of the Hawaiian landscape and biota (Cuddihy and Stone, 1990),large tracts of near-pristine ecosystems remain at high-elevation. Even with the high incidence of extinction and endangerment,Hawaii has more non-endangered endemic species of vascular plants,birds,and insects than any other state except California (Loope,1998). In Samoa,as well as on other high islands of the Pacific (e.g.,the Society and Marquesas,Tonga,the Cook Islands,and the Hawaiian islands) relatively intact biodiversity is centered in high-elevation cloud forests,which may be exceptionally vulnerable to climate change (see box on Montane Cloud Forests).

Caribbean Tropical Forests. The islands in the Puerto Rican Bank have been largely denuded of native vegetation,have extremely dense human populations,and face a formidable array of environmental problems,including extinction of native plants and animals (Wiley and Vilella,1998). The introduction of non-indigenous species,particularly vertebrate animals,is yet another difficulty facing the native plant and animal communities. Still,with increasingly aggressive conservation efforts,Puerto Rico and the US Virgin Islands may retain the best-preserved examples of certain natural ecosystems of the West Indies. Being showcases of natural ecosystems is part of the image of these tropical islands, and is deemed vital to their tourist economies (Wiley and Vilella,1998).

Past policy considerations for tropical forest conservation have generally dismissed the threat of climate change as quite insignificant in comparison to land-use change and other human impacts. However, a better understanding of tropical ecology is now leading many scientists to the conclusion that tropical forests may be very sensitive to climate change. It is being increasingly recognized that factors other than warming,including changes in hydrology, rainfall patterns, and the frequency and intensity of storms and fires, may have far-reaching consequences (Markham, 1998). In comparison to Hawaiian forests, Caribbean forests are well-adapted to disturbance, but increased frequency of hurricanes, floods, droughts, and fires could lead to unprecedented stresses and drastic changes in forest structure and composition. For example, a computer model run for the Luquillo reserve of Puerto Rico showed that increasing intensity of hurricanes could reduce the density of trees in the forest and their total biomass, and favor the development of fast-growing, short-lived and weedy species, including invasive species (O'Brien, et al., 1992).

Mangrove Forests. Coastal wetlands and mangroves of the Caribbean and the Pacific are vital areas for sustaining populations of birds, juvenile fishes, and invertebrates. They also provide important storm and flood buffers between the sea and coastal communities, are coastal stabilizers, and nutrient sinks. Mangrove forests have the capacity to adapt to sea-level rise, although this is being limited by human activities that interfere with forest regeneration. One study suggests that mangrove communities will do better in macrotidal, sediment-rich environments where strong tidal currents redistribute sediment rather than in microtidal, sediment-starved environments, like most small islands (Parkinson et al., 1994). In the pine rocklands (e.g., Sugarloaf Key) in the lower Florida Keys is an area where pine trees grow directly on rock on very low-lying islands. These pines depend on lenses of freshwater that are being gradually eliminated by salt water as sea level rises. The result has been that mangroves have replaced the pines. This transformation will likely continue as sea level rises (Alvarez, 1998). On the other hand, Snedekar (1993) has argued that mangroves in the Caribbean are more likely to be affected by changes in precipitation than by higher temperatures and rising sea levels because they require large amounts of fresh water to reach full growth potential. A decrease in rainfall in the Caribbean could thus reduce mangrove productive potential and increase their exposure to full-strength seawater. (For more information see the Coastal chapter.)

Mangrove trees grow at the land-ocean interface, helping to protect coastal landsfrom erosion. - Source: ©P. Grabhorn

Coral reefs are among the most sensitive ecosystems to long-term climate changes. Source: ©P. Grabhorn

Coral Reefs. It is projected that coral reefs are among the most sensitive ecosystems to long-term climate change (IPCC, 1995). Widespread coral bleaching has already been observed in the Pacific and Caribbean in association with ENSO events and would be expected to continue and accelerate with increased ocean temperatures. Bleaching occurs when the coral animal expels all or part of its symbiotic algae, when the pigments in the algae decline drastically, or when there is some combination of the two. Bleaching is a stress reaction that can be induced by many individual or combinations of conditions: high or low water temperature, high fluxes of ultraviolet radiation, prolonged aerial exposure, freshwater dilution, high sedimentation, or various pollutants (Glynn and de Weerdt, 1991). While low temperatures have generally been considered a limiting factor for the development of coral reefs in cooler climates, reefs are also susceptible to increased temperatures because they are already near their maximum threshold temperatures in summer. While various species and populations may respond differently, in general, coral are likely to bleach but survive if high temperature anomalies persist for less than a month. Such a short-term exposure usually allows corals to recover. However, sustained high temperatures can result in chronic stress that can cause physiological damage that may be irreversible (Wilkinson et al., 1999; Glynn, 1996). Even a sub-lethal stress may make corals highly susceptible to infection by a variety of opportunistic pathogens.

In the late 1980s and 1990s, after localized bleaching in 1982-1983, bleaching became a regular and pervasive problem in the Caribbean and began to appear in the Pacific and Indian Oceans as well. Bleaching occurred in American Samoa during the warm event of spring 1993. During the El Niño of 1997-1998, bleaching began in the eastern Pacific but then expanded to an unprecedented depth and region across to and including the Indian Ocean, and in the Pacific Ocean from Australia to Polynesia. Bleaching was widespread in the Republic of Palau during the 1997-1998 El Niño.

Corals in the Caribbean are currently impacted by enormous numbers of international tourists, high volume of ship traffic, and fishing. Pacific Ocean coral reefs are some of the world's healthiest overall; about 70% are rated in good-to-excellent condition. But 30% are rated fair-to-poor and many are dying, while human impacts are growing. The region's extremely diverse corals, mangroves, and sea-grasses are pressured by deforestation, agriculture, construction, pollution, and fishing. Climate-related changes could affect coral through more than simply increased water temperatures: in some Pacific jurisdictions, changes are expected in aerial exposure due to sea-level alterations associated with ENSO. In the Caribbean, erosion/sedimentation may be caused either directly through floods or indirectly through increased erosion following fires associated with drought conditions. In addition, hurricanes and typhoons can damage coral reefs. For example, Hurricane Hugo in 1989 caused extensive damage to reefs outside of Puerto Rico by fragmenting, overturning, or destroying virtually all elkhorn coral colonies that were over one meter in size (USGS, 1999). Elkhorn coral are a principal reef builder. Unhealthy coral reefs are the most susceptible to destruction by hurricanes and typhoons. Effects of increasing atmospheric carbon dioxide

Montane Cloud Forests: Unique and Vulnerable Ecosystems

The tropical montane cloud forests of islands are rare, diverse, and vulnerable natural habitats, occurring in such Pacific islands as the Society and Marquesas islands, Cook Islands, Tonga, Samoa, and the Hawaiian Islands as well as elsewhere in the world (e.g., Madagascar, Sri Lanka, Greater and Lesser Antilles). The upper and lower limits of cloud forest vegetation are determined by the altitude of a persistent cloud zone. The upper limit of this zone is generally set by the elevation of the trade wind inversion and the lower limit is determined by temperature and humidity. Cloud forests are likely to be extremely sensitive to climate change. These unique forest environments would be affected by any potential changes in the altitudinal level of the trade wind inversion, as well as changes in temperature, precipitation zones, increased drought, or hurricanes. On high islands such as Maui and Hawaii, the two largest of the Hawaiian islands, the cloud forest vegetation now changes abruptly to grassland or shrubland above the mean elevation of the inversion layer.

The Hawaiian anianiau (*Hemignathus parvus*) an endangered species, is now restricted to high elevation montane rain forest on Kauai. Like other native Honeycreepers, it is highly susceptible to avian pox and malaria, and as a result of mosquito transmitted bird diseases the Anianiau has disappeared from its former low elevation habitats. Source: (http://water.usgs.gov/pubs/FS/FS-012-99/)

Loope and Giambelluca (1998) have identified Pacific island cloud forests as particularly vulnerable to human-induced climate change, since relatively small climate shifts are likely to trigger major local changes in rainfall, cloud cover, and humidity. Such climatic disruptions will undoubtedly favor the penetration of invasive non-indigenous species into previously intact ecosystems. Pounds et al. (1999) have already demonstrated a constellation of population crashes of native birds, reptiles, and amphibians in biological communities in the montane cloud forest of Monteverde, Costa Rica, apparently resulting from oceanic and atmospheric warming and drying in the extreme eastern tropical Pacific.

The cloud forests of East Maui, Hawaii (Haleakala National Park and neighboring reserves), for example, are home to numerous endemic species, with approximately 90% of the native flowering plants and invertebrates endemic to Hawaii. Nine endemic bird species in the Hawaiian honeycreeper family occupy these cloud forests. One reason these birds survive in the higher forest is because the mosquitoes that carry avian malaria are limited at higher elevations by cooler temperatures. Therefore, any warming that allows the mosquitoes to move farther up the mountain may threaten the birds, five species of which are already listed as endangered by the US Fish and Wildlife Service. (From Loope, personal communication.)

concentrations could also possibly have adverse effects on reef building corals (see Coastal chapter for details). Without the reefs,low-lying islands would be susceptible to rapid erosion and destined to eventual disappearance.

Adaptation Options

There are a limited number of specific options that can be employed to assist island ecosystems to cope with a changing climate. Some of those options include the following:attempting to slow biological invasions;strengthening and enforcing policies that protect critical habitats;improving understanding of the local effects of climate variability and change;and increasing awareness of tourists and the public concerning the value of species and biodiversity.

4. Sea-Level Variability

Sea-level rise and the associated erosion and inundation problems are currently extremely important issues for many of the US affiliated islands. There are two factors that affect the impacts of sea-level rise on islands:the rate and extent of global sea-level rise and the occurrence of episodic events,such as extreme lunar tides,ENSO related changes,and storm-related wave conditions. Rising sea levels over the past century have already resulted in salt water intrusion into freshwater lenses,inundation of coastal vegetation (such as taro,pulaka,and yams), and coastal erosion,since a typical beach erosion rate can be 150 times the amount of sea-level rise (Alvarez,1998). The Gulf and Caribbean region

Pacific Island Observed Sea-Level Trends

(based on Merrifield,personal communication)

Location/Name	Observed Rise in Relative Sea Level (averaged forthe 20th century)	Years of Data Collection
Hawaii		
Hilo	13.6 +/- 2 in (34 +/- 5 cm)	1927- 1999
Honolulu	6 +/- 0.8 in (15 +/- 2 cm)	1905- 1999
Nawiliwili	6 +/- 1.6 in (15 +/- 4 cm)	1954- 2000
Kahului	8.4 +/- 2 in (21 +/- 5 cm)	1950- 1999
Mokuoloe	4 +/- 2 in (10 +/- 5 cm)	1957- 1999
Guam	0 +/- 2.4 in (0 +/- 6 cm)	1948- 1999
American Samoa		
Pago Pago	6.4 +/- 2.4 in (16 +/- 6 cm)	1948- 1999
Commonwealth of Northern Marianas		
Saipan	-0.4 +/- 8.8 in (-1 +/- 22 cm)	1978- 1999
Republic of the Marshall Islands		
Wake	7.2 +/- 2 in (18 +/- 5 cm)	1950- 1999
Kwajalein	3.6 +/- 1.6 in (9 +/- 4 cm)	1946- 1999
Republic of Palau		
Malakal	- 1.6 +/- 7.2 in (-4 +/- 18 cm)	1969- 1999
Federated States of Micronesia		
Kapingamarangi	-6.4 +/- 9.2 in (-16 +/- 23 cm)	1978- 1999
Pohnpei	6.4 +/- 7.2 in (16 +/- 18 cm)	1974- 1999
Yap	-5.6 +/- 7.2 in (-14 +/- 18 cm)	1969- 1999

A typical beach erosion rate can be 150 times the amount of sea-level rise. Source: ©P. Grabhorn

experienced on average a relative sea-level rise of 3.9 inches (10 cm) during the 20th century. In the Pacific region, as around the globe, absolute sea level is also rising. There is, however, a great deal of inter-island variability in relative sea level (see table). This occurs because a number of Pacific Islands are rising due to geologic uplift. As a result of this uplift, relative sea-level changes for those islands can appear to be negative. The Pacific regional averages can, therefore, tend toward zero depending on which islands are included in the average; hence, the global sea-level trend is not evident in the long-term average trend in relative sea-level in the Pacific (Merrifield, personal communication).

Long-term global rates of sea-level rise are projected to be 2 to 5 times faster in the 21st century than during the 20th century. Future sea-level rise, both global and episodic (since increasing global sea level will also raise the level from which episodic events occur), will increasingly contribute to negative consequences for populations and ecosystems (Titus et al., 1991).

Risk of flooding, inundation, and coastal erosion on particular islands depends on both physical properties of the island (elevation, rock and soil-type, location) and on biological properties (presence or absence of biotic protection such as coral reefs and mangroves). The most at-risk island types are low-lying coral atolls because of both their elevation and composition. The vulnerability of specific sites depends on the value of what is at risk, including such aspects as natural resources, transportation and social infrastructure, businesses, and human populations. Among other factors, sensitivity increases because of dependence on coastal activities for their economies, dependence on coastal aquifers for freshwater supply, the presence of culturally valued structures along the coast, or because of previous land-use changes. Ultimately, vulnerability to sea-level rise is a function of both the natural resilience of the shoreline and biological resources, as well as the value of the resource at risk, and the ability of human populations to respond and implement adaptation measures and strategies. Vulnerability also depends on the timeframe over which recovery is possible and the resources that are available.

Islands will be particularly vulnerable to sea-level changes and consequent impacts if they are low-lying and have limited resources for protecting their coastline. In the Pacific, potentially vulnerable island groups include the atolls of the Republic of the Marshall Islands and the Federated States of Micronesia. In the Caribbean, much of the metropolitan area of San Juan in Puerto Rico is already close to sea level. Islands that are high volcanic or limestone, mountainous, naturally rising, or lack resources and populations in coastal areas will be less vulnerable.

Adaptation Options

Coping with sea-level change and the resulting consequences (e.g., flooding, inundation of freshwater and agricultural systems, erosion, destruction of transportation and other built infrastructure) will require a variety of strategies. Some of the options that are likely to be needed could include: protecting coastal infrastructure (both social and transportation), water systems, agriculture, and communities; integrated coastal zone management; and crop shifts and the use of salt-resistant crops. Retreat from risk-prone, low-lying areas is also likely to be necessary in some cases, but will be complicated due to land ownership, and could have significant consequences for social and cultural identity.

For more details on projected sea-level rise and its impacts, see the Coastal chapter in this volume and the additional volume: The Potential Impacts of Climate Change on Coastal and Marine Resources: Report of the Coastal and Marine Resource Sector Team of the US National Assessment.

ADDITIONAL ISSUES

Climate variability and change present island governments, businesses, and communities with challenges and opportunities in a number of other key areas including:

Tourism

Tourism remains a significant contributor to the economies of the Caribbean islands, the State of Hawaii, Guam, and the Commonwealth of the

Northern Mariana Islands, and is considered to offer economic growth potential for many of the jurisdictions addressed in this chapter. Unique ecosystems (both terrestrial and marine) and attractive coastal areas are among the natural assets that draw tourists to the islands of the Pacific and Caribbean. These natural assets are already under stress as a result of pollution and the growing demands of an increasingly coastal population. Many of the projected climate changes for the islands would exacerbate numerous of the stresses that the islands are already under. For example increasing rates of sea-level rise would contribute to: sea water inundating low-lying areas and threatening key infrastructure (including airports and roads); increasing the risks of damage from tropical storms (particularly damages associated with storm surge); threatening coastal water supplies through salt water intrusion; and reducing the extent and quality of sandy beaches through both inundation and increased erosion associated with storm surge. The South Atlantic Coast-Caribbean workshop report suggests that at the present rate of sea-level rise, there is already a loss of 9 feet (2.7 meters) of coastline due to erosion every decade, in some areas. The projected increased rate of sea-level rise would produce over 33 feet (10 meters) of erosion per decade since a typical beach erosion rate can be 150 times sea-level rise.

Other climate-related changes of concern to tourism include: changes in tropical storm patterns; changes in temperature and rainfall patterns with attendant consequences for terrestrial ecosystems and animals; and changes in ocean temperature, circulation, and productivity that could affect important marine resources like coral reefs and the fish they support. In addition, the climate itself is a magnet for tourists. Locations could become undesirable to tourists because of detrimental temperature and comfort-level changes. It is also evident that just the threat of some impacts has caused tourists to plan vacations or conventions elsewhere.

Fisheries

Climatic conditions influence where specific species can live, grow, and reproduce. The appropriate temperature ranges of some fisheries are extremely narrow and as a result they are sensitive to even small temperature variability within their ranges. Recent scientific studies are demonstrating an important link between patterns of natural climate variability, such as the ENSO cycle, and the migratory patterns of important pelagic species like tuna. Hamnett and Anderson (1999), for example, suggest that the eastward expansion of warm water in the Pacific during an El Niño is associated with an eastward displacement of Skipjack tuna stocks. As global patterns of water temperature change, species shifts can be expected to follow these changes.

Climate variability and change present a number of challenges for coastal and marine fisheries that remain significant components of the culture and economies of many of the island jurisdictions addressed in this chapter. The movement of the commercially-important Skipjack tuna noted above resulted in the stocks being closer to the Marshall Islands and away from the waters of Micronesia. Industry representatives in FSM noted reduced catches in late 1997 and early 1998 (coinciding with the 1997-1998 El Niño), while government officials in the Marshall Islands noted an increase in fishing activity within their waters in late 1997, resulting in greater access fees from vessels within their Exclusive Economic Zone.

Changes in the ENSO cycle or other climate-related changes in ocean circulation and productivity could bring significant changes to the location of tuna stocks, thus providing opportunities for those jurisdictions that find themselves close to large stocks, and problems for other jurisdictions that find themselves far away from commercially-important species. For many of the Pacific island jurisdictions addressed in this National Assessment, the development of a viable tuna industry is considered an important component of their economic growth. StarKist Samoa and Samoa Packing, for example, are two of the largest tuna canneries operating within the US and they are the largest private sector employers in American Samoa. Fishing access/license fees from Distant Water Fishing Nations catching tuna in the FSM's Exclusive Economic Zone are a major source of revenue for the country (constituting a 17% share of the national GDP in 1994). Further development of that industry is currently the primary focus for economic development in FSM.

In addition to their importance to the tourism industry, many inshore species, including a number of reef fish, remain important contributors to the subsistence diet in small island communities. Any climate-related changes in the habitats that support these fisheries would have consequences for those communities.

Agriculture

Agriculture, for both commercial and subsistence purposes, remains an important part of the economies of many of the island jurisdictions addressed in this National Assessment. Much of the most productive agricultural land on these islands is located in low-lying coastal areas that are at-risk from climate-related changes in sea level. In addition to problems associated with inundation, saltwater intrusion associated with sea-level rise would also present challenges to agricultural production unless appropriate salt-tolerant species could be utilized. Climate-related changes in rainfall and tropical storm patterns also present problems for agriculture in island communities as evidenced by the impacts of the 1997-1998 El Niño event in the Pacific. For example, agriculture in all Pacific Island jurisdictions affiliated with the US except Guam suffered as a result of the droughts associated with the 1997-1998 El Niño event. In Yap, taro losses were estimated at 50-65% and over half of the banana trees evaluated on Pohnpei had died or were seriously stressed. Agriculture in Guam, on the other hand, suffered substantially from the El Niño-induced Typhon Paka that occurred in December 1997.

Data Collection and Availability

One other issue of concern to the islands relates to the complexities of data collection, availability, and reliability, both for climate data and impact studies. These data are necessary to enhance the ability of scientists and decision makers throughout the island regions to understand and respond to the challenges and opportunities presented by changes in climate and other critical environmental conditions.

Climate prediction data availability is at times limited for islands because most climate models in use today are unable to effectively capture island-scale or sub-island scale processes. Also, geographic isolation and dispersion makes data collection and research in island settings, particularly the Pacific, costly and difficult. The harsh environments affecting most islands pose related difficulties in maintenance of monitoring stations. At the same time resources for small-scale, locally-based research focused on individual islands or island ecosystems are difficult to secure, especially since many of these ecosystems are unique and, therefore, research results tend to have more local than global significance. Another difficulty is related specifically to impacts research where many impacts investigations are undertaken by non-local scientists who too often fail to capture/integrate valuable information associated with traditional knowledge of specific island cultures. In the case of many of the islands, the communication and information management infrastructure is limited and already stressed. Establishing and maintaining an interactive dialogue between scientists and beneficiaries of their work outside the scientific community will require both technological upgrading and institution of a new paradigm of collaboration and integration of information related to climate changes and their impacts. These challenges point to a significant need for local capacity building (e.g., technical training in data gathering, monitoring technology, information distribution, impacts research, and communication technologies).

ADAPTATION STRATEGIES

Overall, strategies helpful for islands to cope with climate variability and change involve a wide range of options. While identifying many of the possible options is an important part of this Assessment, it is only a first step. It was not possible at this time to evaluate any of these potential options for practicality, effectiveness, or cost. Nevertheless, some potential adaptation options for the islands include: increased use of climate forecasting capabilities; consideration of changes in land use policies and building codes; use of new and emerging technologies to both mitigate the causes and reduce the impacts of climate change; increased monitoring, scientific research, and data collection abilities; and improved management policies. In addition, broad public awareness campaigns and communication with user groups are important mechanisms for improving public health and safety, and protecting natural resources.

Land-use policies and building codes can mitigate flood conditions (from sea-level rise as well as from extreme precipitation events) and can encourage construction in areas where life and property will not come into danger from floods, landslides, and severe storms including storm surge. Implementing such land-use policies could be an important coping option. Planting of trees and reforestation encourages natural infiltration, which increases underground water resources and prevents runoff that can lead to flood conditions. Building and transportation infrastructure can be renovated or replaced in the natural renewal cycle with higher standards. It is important to protect the species and ecosystems that currently exist and find strategies to limit sprawl and population growth that are impacting presently healthy ecosystems.

Possible Climate Change Adaptation Options

as identified by the Federated States of Micronesia

Water Resources	• Conduct a comprehensive inventory of existing water resources • Assess the status of storage and distribution systems and secure resources for necessary improvements. • Encourage improvements to residential and commercial catchment systems and identify/support new technology. • Identify opportunities to adjust water conservation and management policies to incorporate information about climate variability and change. • Document the experience gained during the 1997-1998 El Niño and build on the concept of drought management task force(s) to assist governments,communities,and businesses in responding to climate-related events. • Identify opportunities to improve watershed management.
Coastal Resources	• Identify buildings,infrastructure,and ecosystems at risk and explore opportunities to protect critical facilities. • Develop and implement integrated coastal management objectives that enhance resilience of coastal systems to climate change and sea-level rise. • Consider the need for beach nourishment and shoreline protection programs in high-risk areas. • Integrate considerations of climate change and sea-level rise in planning for future construction and infrastructure.
Agriculture	• Document the experience gained during the 1997-1998 El Niño and build on the concept of drought management task forces to assist governments,communities and businesses in responding to climate-related events. • Develop policies that protect both subsistence and commercial crops during extreme events. • Explore opportunities to diversify crops and select drought and/or salt-tolerant species where appropriate. • Document low-lying agricultural areas at-risk from the effects of sea-level rise and consider protection measures where appropriate and necessary.
Fisheries	• Enhance data collection and analyses required to improve understanding of the impacts of El Niño and La Niña events on tuna and other critical fisheries. • Identify and protect critical habitats for key inshore and near-shore species,particularly those important for subsistence fisheries. • Support monitoring and monitoring programs designed to improve understanding of the regional and local consequences of climate variability and change for tuna and other important fisheries.

From the National Communication to the United Nations Framework Convention on Climate Change,October 1999.

Improved technologies and water conservation are critical for protection of water resources. These include more and better rainfall catchment systems, improved storage and distribution systems,artificial recharge of aquifers,and desalinization. In addition, it is important for communities to take advantage of new capabilities in climate forecasting which, among other advantages,can allow for preparation for water scarcity conditions.

Improved management is critical for both ecosystem and human system protection. This includes more efficient management of existing water supplies,active management of natural areas,attention to policies that attempt to slow biological invasions, increased disaster response planning,and appropriate land uses.

At the regional workshops,participants advocated for effective,unified planning and response systems, and for incorporating climate change in growth management regulations. In particular, they stressed the need to design solutions that will be accepted by the local communities,and the need for coordinated institutional structures to manage the coastal resources. An example of a regional response plan for the Federated States of Micronesia is shown in the table opposite.

CRUCIAL UNKNOWNS AND RESEARCH NEEDS

To more effectively evaluate the potential consequences of climate variability and change impacts on Islands,a number of research needs have been identified by the Pacific and Caribbean workshop participants. The following is a brief listing of some of the identified research needs:

- Regional-scale information on changes in water availability, frequency, and intensity of extreme events such as hurricanes or typhoons,and interannual variability of climatic factors such as ENSO; specifically, downscaling by nesting regional climate models within global models.

- How to build local capacity to use such regionally-focused nested models and other data collection techniques and to interpret the information into useful products for island decision makers and island populations;

- How identified key parameters affect communities,the built infrastructure including transportation aspects,businesses,and economic sectors,as well as critical habitats and natural resources;

- The value of forecasting and understanding climate variability and change and how that understanding supports stakeholders in decision making processes;

- Environmental and socioeconomic changes on islands and how the two are related to one another; the interactions of multiple stresses;and identification of the specific parts of society that are most vulnerable to climate change and variability;

- An assessment of the status quo related to water resource management,health care systems,and emergency systems;

- Implications of potential climate-change-response policies for islands and island economies;

- How to improve risk analysis,monitoring systems, and evacuation systems on islands;and

- The impacts of changes in sea level,both short-term variations and long-term trends,on freshwater supply and other potential threats to coastal communities and ecosystems;

- How to incorporate appropriate traditional knowledge and response strategies into response options.

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